Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2001-611

On-Board Decision Support through the Integration of Advanced Information Processing and Human Factors Techniques
The POWER Project

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Summary

As advanced crew support technologies will be available more and more in future military aircraft, it is necessary to have a good understanding of the possibilities in this area, taking into account operational demands, technical possibilities, human factors, evaluation, and validation aspects. A Crew Assistant (CA) is a decision support system for air crew, designed to improve mission effectiveness and redistribute crew workload in such a way that the crew can concentrate on its prime tasks.

The POWER (Pilot Oriented Workload Evaluation and Redistribution) project is a Netherlands National Technology Project. The project is aimed at demonstrating a generic CA environment and individual tactical decision support tools to military pilots in a simulated environment, the NSF (National Simulation Facility), a six-degrees of freedom cockpit in a visual dome.

The project is a technology demonstration project to show new CA features. An advanced software architecture has been set up, based on multi-agent technology, where software "agents" co-operate in sharing information and using resources on an as-needed basis. Each agent is an autonomous piece of software that is able to anticipate courses of action and performs its function pro-actively.

Several prototypes of crew assistant agents have been developed and integrated in order to facilitate a CA demonstrator and a large-scale experiment with operational pilots from the Royal Netherlands Air Force (RNLAF) has been carried out to demonstrate the effects of CA technology as decision support, to validate tools, and to measure the effects of on-board decision support in enhancing pilot situational awareness.

The prototypes and experiments have proven the benefits of demonstrating the technology to pilots; after initial scepticism, they felt confident with using the tools after a while without being afraid to loose their skills for manual actions. The experiments also proved the benefits of Crew Assistant tools with respect to mission effectiveness and tactical task accomplishment in highly complicated situations. From a technical perspective, the possibility for real-time and any-time on-board reasoning was proven.

This paper describes the demonstration CA environment and provides insight into the different CA components. Part one describes the environment as a generic CA architecture that can be installed on a simple work station as well as in a full-scale simulation environment. The second part of this paper describes the aforementioned experiment, where the NLR Counter Measure Manager (NCMM) and the contents of the experiment will be detailed.

Abbreviations

AI	Artificial Intelligence
AIP	Advanced Information Processing
CA	Crew Assistant
CAMA	Crew Assistant Military Aircraft
CASSY	Cockpit Assistant System
CTM	Counter Measure Technique
COGPIT	Cognitive Cockpit
DERA	Defence Evaluation Research Agency
DoD	Department of Defence
ECG	Electrocardiogram
ECOP	Electronic Co-pilot
EPOG	Eye Point Of Gaze
EUCLID	European Co-operation for the Long Term in Defence
EW	Electronic Warfare
HF	Human Factors
HMI	Human Machine Interface
HR	Hart Rate
HRV	Hart Rate Variance
MAW	Missile Approach Warning
MFD	Multi Function Display
MLU	Mid Life Update
MLW	Missile Launch Warning
MSDF	Multi-Sensor Data Fusion
NADDES	NLR Avionics Display Development and Evaluation System
NCMM	NLR Counter Measure Manager
NLR	National Aerospace Laboratory (Nationaal Lucht- en Ruimtevaartlaboratorium)
NSF	National Simulation Facility
PA	Pilot's Associate
POWER	Pilot Oriented Workload Evaluation and Redistribution
RCM	Reflex Counter Measure
RGPO	Range Gate Pull Off
RNLAF	Royal Netherlands Air Force
RPA	Rotorcraft Pilot's Associate
RWR	Radar Warning Receiver
SAM	Surface to Air Missile

Contents

(30 pages in total)

PART I: A CREW ASSISTANT ARCHITECTURE

1 Introduction

Software and human factors are becoming major part of current and future on-board avionics. Current developments in software engineering and advanced information processing techniques enable complex crew assistant applications, especially support of the aircraft crew in carrying out primary and secondary tasks is more and more provided by electronic systems. Application of crew assistants in fighter aircraft is a challenging task, both for the research and development of the software, as for the human factors aspects concerning its optimal use and trust of the pilot in the system.

The POWER (Pilot Oriented Workload Evaluation and Redistribution) project, is a Netherlands National Technology Project. The project is aimed at demonstrating a generic Crew Assistant (CA) environment and individual tactical decision support tools to pilots in a simulated environment, the NSF (National Simulation Facility), a six-degrees of freedom F-16 cockpit in a visual dome. This demonstrator has been the focus of the project.

Current progress in advanced information processing, new advances in human factors, and the possibility to validate new avionics so that pilots learn to trust the system, form the basis for this paper in order to support RNLAF in the acquisition and usage of new aircraft. In this paper, a generic simulation environment is discussed, that enables different levels of crew assistant demonstration and experimentation. The environment proposed is based on multi-agent technology, where a generic Crew Assistant environment can be plugged onto a "simple" scenario generator on a work station or to a full-scale flight simulation facility, like the NSF.

Several prototypes of CA agents have been developed and integrated in order to facilitate the CA demonstrator:

- A profile recognition agent takes input from different sensors and recognises profiles in a data fusion assembled picture. The agent reasons with uncertainty in the observation and uses Bayesian Belief Networks to model the profile and sensor's characteristics.
- A manoeuvre prediction agent assesses an opponent's manoeuvre and predicts the patters that will be flown when in air-to-air combat. This tool is based on case-based reasoning technology.

- The NCMM (NLR counter Measure Manager) agent advises counter measures against threats, e.g. SAM-sites. The tool is based on expert system technology.
- An HMI is designed with an NLR built tool, NADDES (NLR Avionics Display Development and Evaluation System), for increasing pilot situation awareness.

This paper will provide an overview of the POWER project. It has been set up in two parts, where the first part describes the generic CA architecture and part two describes a large scale experiment that has been carried out. Chapter two will introduce crew assistant technology and chapter three will describe the software architecture, which is based on multi-agent technology. Chapter four describes the technical aspects of the simulation environment the experiment. Chapter five describes the setting and results of this experiment.

2 Crew Assistant Technology

Fighter pilot's workload is rapidly increasing. Modern military operations take place in a complex environment to accomplish a spectrum of missions. The most important factor in the increase in workload concerns the operational environment of current fighter aircraft:
- The increase of the complexity of the military environment in general (e.g. combined joint task forces, peace keeping/peace enforcement).
- The increase of the complexity of the types of missions to be flown.
- The increase in the number of different (kinds of) threats.

Another factor is the technological developments of fighter aircraft. The increase in aircraft speed and aircraft types and on-board systems causes the aircraft itself to become much more difficult to manage, putting more pressure on the crew. During high-stress situations, the crew can get overloaded with information, while it has to perform a multitude of actions. Figure 1 illustrates the possible information overload and decision making process.

A Crew Assistant is an on-board decision support system that supports the crew in performing its mission. It aims at improving mission effectiveness, flight safety, and/or survivability by providing the crew with concise and relevant information, depending on the mission phase, thus enabling the crew to concentrate on mission decisions and make more effective decisions. [Urlings 1995]. In essence, Crew Assistants change the nature of the information that sensors provide to enable decision making, hence "information" is transferred to "knowledge". Crew Assistants are decision support systems for air crew, designed to improve mission effectiveness and redistribute crew workload in such a way that the crew can concentrate on its prime tasks. Ideally, a CA assists a pilot, or other crew members, by providing the following kind of functions:

- Acquire the necessary information and merge the input from different sensor and information systems into one timely and consistent view of the current situation (the status of different on-board systems, the situation outside, etc.).
- Process the merged information to give advice (weapons selection, route planning, tactics evaluation, fuel management, etc.).
- Perform tasks autonomously when so instructed by the pilot or another crew member (autopilot, target tracking, systems monitoring, etc.).

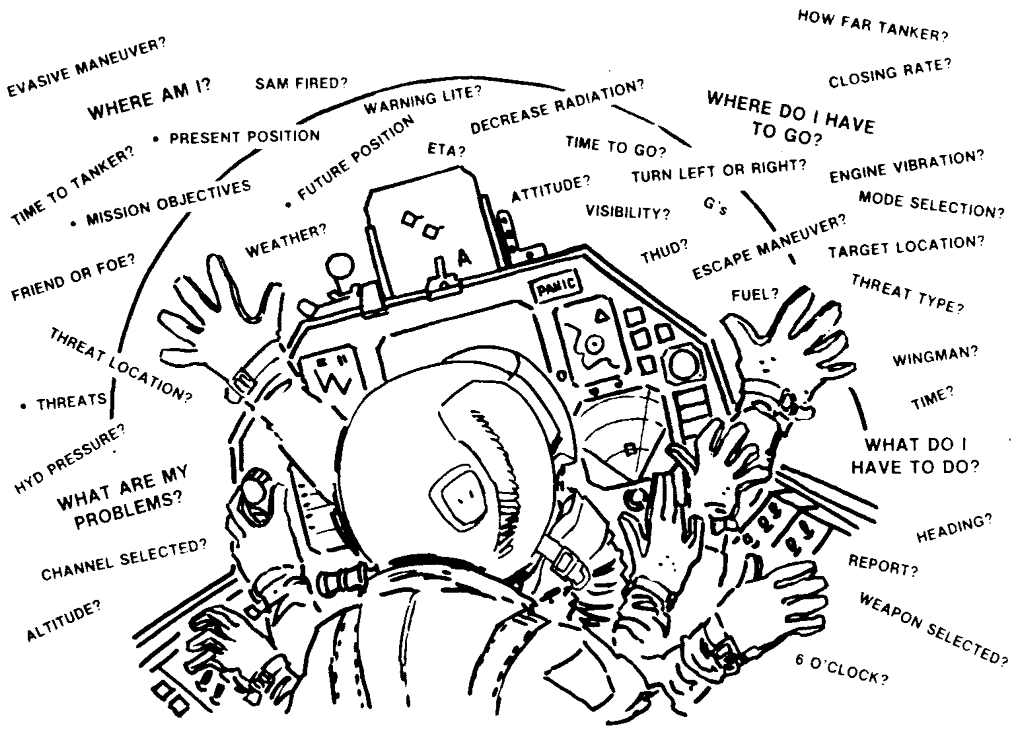

Figure 1. The information requirements of the crew [Yannone, 1985].

As advanced crew support technologies will be available more and more in future (military) aircraft, it is necessary to have a good understanding of the possibilities in this area, taking into account operational demands, technical possibilities, human factors, evaluation, and validation aspects.

The current state-of-the-art in advanced information processing now makes intelligent pilot assistant through a CA technically feasible, including real-time on-board data acquisition, fusion, and processing. Advanced information processing techniques, like expert systems and neural networks, and methods for constraint reasoning, case based reasoning and reasoning with uncertain and incomplete information, can be used in the military cockpit. Research in Human Factors technology aspects, will make the techniques available to the human operator. For an overview of systems and technologies, see e.g. [Boers 1999], [Van Gerwen 2000-1], [Verhoeven 2000].

In the course of the years, several CA programs have been set up. The Crew Assistant Military Aircraft (CAMA) is a German DoD programme that investigates the use of an intelligent electronic crew member in the military transport application [Strohal 1997], [Frey 1999]. Within the programme, flight simulator trials have been performed in the simulator of the University of the German Armed Forces. Flight experiments are scheduled in an in-flight simulator. Hands-on experience and feed back from pilots is a factor in the development of systems that must be gained. One project that takes a human factors perspective on CAs is the Cognitive Cockpit (COGPIT) project, that has been set up by the UK Ministry of Defence in conjunction with the Defence Evaluation Research Agency (DERA). This project seeks to develop a theoretically grounded, human-centred approach for guiding a principled development of intelligent pilot aiding concepts for cockpit automation [Taylor 1998], [Taylor 2000]. It researches the cognitive engineering aspects of the pilots to couple knowledge-based systems for situation assessment and decision support with concepts and technologies for adaptive automation and cockpit adaptive interfaces. Other CA projects are Pilot's Associate (PA) [Holmes 1991], Rotorcraft Pilot's Associate (RPA) [Collucci 1995], CoPilote Electronique, Cockpit Assistant System (CASSY) [Onken 1997], and the Electronic Co-pilot (ECOP) [Stein 1987].

These programs take either a technological or a human centred focus on CAs. We believe that for a good integration of CA technology in the cockpit, the relationship between the fields of Advanced Information Processing (AIP) and Human Factors (HF) should be exploited further. The POWER project brings together the fields of military operations research, advanced information processing and human factors. It combines techniques from artificial intelligence and human machine interaction in such a way that pilots are supported with advanced crew assistants, wherewith the information is provided to them in a sense that a fused picture of the world emerges. Apart from the technological aspects, the POWER project has strong roots in the analysis of requirements and needs from operational fighter pilots. The project will help decision makers in technology assessments for acquiring new aircraft and equipment and manufacturers in making strategic decisions on technological programmes.

In many cases, information will be time dependent, inaccurate and incomplete. The use of uncertain and incomplete information should be further investigated and must be considered in the design of the Human Machine Interface (HMI). The project therefore, focuses on the following challenges:

- Provide a flexible demonstration environment for crew assistant technology, based on operational demands from fighter pilots.
- Provide examples of crew assistant technology, based on new advanced AIP and HF aspects.
- Provide insight in new real-time reasoning techniques for reasoning with uncertainty.
- Provide a quantitative scientific base that proves the benefit and user acceptance of CA technology.
- Perform experiments with the demonstration environment that lays a basis for further work in the field of introducing CA technology to the RNLAF.

3 The Architecture

Until recently, work in on-board automation focussed on the introduction of single self-supporting functions. The advantage of this is high reliability in case of single failures, where other independent systems take over. Instead of relying on the information that one sensor provides, CA decision support functions in essence focus on the integration of information and the provision of a complex and fused picture to the pilot. This creates new demands for the software and hardware architecture and the human factors aspects.

Decision support functions are concerned with data acquisition, fusion, and processing and use information from different sources, so that an architecture is needed, where the system does not rely on one information source and does not contain any critical processing nodes. We believe that an architecture based on agent technology can and will play an important role in the near future in avionics. Agent-based architectures have been introduced for on-board decision support systems in e.g. TANDEM [Barrouil 1999], the Cognitive Cockpit [Taylor 2000], and for on board multi-sensor data fusion [Bossé 1999].

The strength of software agents is that they can be made to interact with other software agents or human users. Agents are “small” autonomous black boxes, which handle their own clearly defined tasks. A system of agents that co-operates is called a multi-agent system. Agents, if well-designed as separate processing units, enable communication between multiple subsystems, without putting a strain on one specific part of the system. Their loose coupling provides a possibility to introduce new technology throughout the aircraft's lifetime, especially at "end of the line" functions, like weapon systems, where it is relatively easy to validate new technology.

This chapter will give an overview of the proposed multi-agent architecture and will describe the most important CA components that have been provided with the POWER project.

3.1 A Functional Architecture based on Multi-Agent Technology

The proposed architecture has been based on the results of earlier projects, like the EUCLID (European Co-operation for the Long Term in Defence) Research and Technology project 6.5 [Zuidgeest 1995]. This NLR-led project on CAs for military aircraft started with extensive user interviews to establish an inventory of operational user problems and needs for pilots flying F-16, Tornado, and AM-X. The project came up with a generic on-board CA architecture and indicated a challenge in the application of multi-agent systems and knowledge based systems.

The architecture that has been set up for the POWER project distinguishes four groups of functional agents. The groups are (1) data and information input agents, like sensors and the multi-sensor data fusion agent, (2) data processing agents which form the actual crew assistant functions, (3) information output agents mainly to the pilot, and finally, (4) the weapon agents. Apart from these, other agents perform functions for controlling and monitoring the overall system's status and health. In this paper, we will focus on the functional part of crew assistants, see figure 2.

The four functional groups further subdivided in seven subgroups (see slight colour differences in figure 2), discussed below.

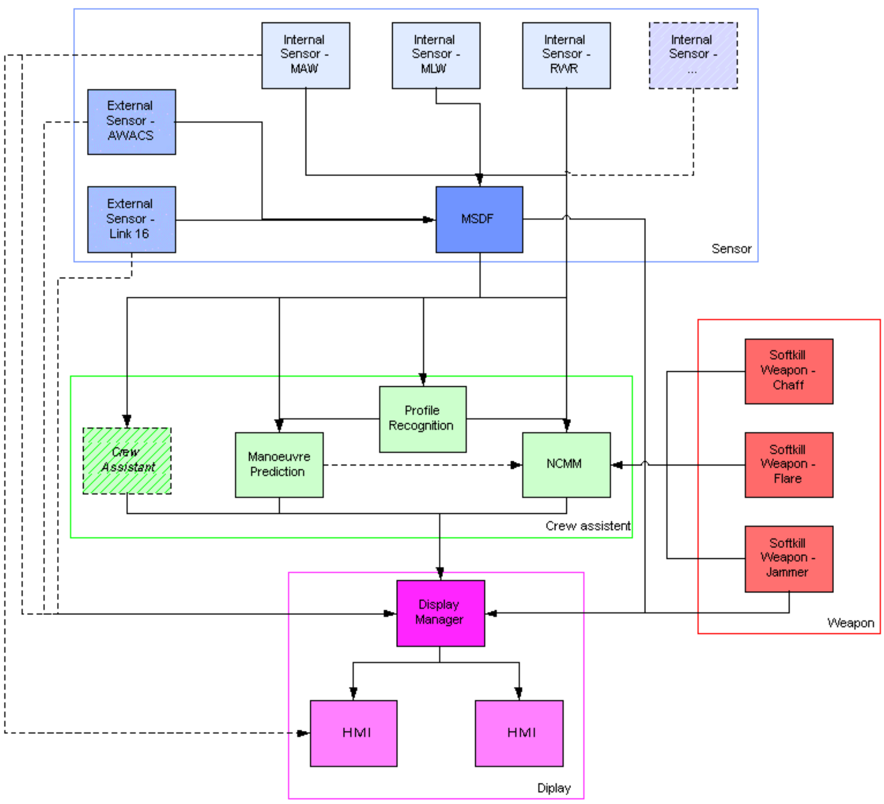

Figure 2. Functional architecture of on-board agents

Internal sensor agents are system components that transform the raw input data from the sensor hardware to an understandable format for the Multi-Sensor Data Fusion (MSDF) component. In our example, we included sensors to detect and distinguish SAMs and to detect incoming missiles.

- A Radar Warning Receiver (RWR) provides the position of ground threats, including an indication whether the SAM is in search, track, or guidance.
- The Missile Launch Warning (MLW) is a passive infrared plume detector that provides missile information while its motor is burning.
- The Missile Approach Warning (MAW) is an active short range radar that detects a missile body, usually in a two to three miles range.

External sensor agents are components that obtain their information from sensors or information systems that are physically located outside the aircraft, for example an AWACS or a Link-16. These sensor agents transform data and information into an understandable format for the MSDF agent or for the CA agents.

The Multi-Sensor Data Fusion agent combines the sensor information from all internal and external sensors into a combined sensor data picture. This agent may perform complex situation assessment tasks. In the current implementation, this is a fusion process that only provides the information to the CA's that is really necessary for the CAs to perform their task. Different projects have already shown the complexity of a multi-sensor data fusion process and have proposed architectures [TA-10], [Bossé 1999]. The latter proposes an agent based architecture for multi-sensor data fusion, which shows the flexibility of agent systems, where agents can delegate tasks to (sub-)agents.

Crew Assistant agents are the intelligent pilot support functions. The ones mentioned in figure 2 are elaborated in the POWER project (based on [Zuidgeest 1995]), however, the range of pilot support functions is not limited to these. CAs can be further classified into functions as information finding in the fused sensor picture (like profile recognition, see section 3.2), pilot advice (like manoeuvre prediction, see section 3.3, and NLR's Counter Measure Manager, see section 3.4 and chapter 4), pilot monitoring, mission monitoring, etc. Other classifications are possible, like [Barrouil 1999], [Taylor 2000].

Weapon agents control the weapon delivery. In this example, a number of softkill weapons to countermeasure ground threats is displayed. Their intelligence for example consists of providing the correct jamming against a recognized threat or dispensing a complex pattern of chaff and flare.

The Display agent is responsible for assembling an integrated picture of crew assistant information and for prioritizing information provision to the pilot. If necessary, it can hold information that is considered less important at a certain moment or less time critical, if the pilot is assumed to get overloaded with information. Once the situation is more relaxed, it can decide to provide this information. An even more intelligent display agent can decide what information should be provided on which cockpit display, or what information should be provided on which part of the cockpit display and automatically adapt the contents of the available displays if at (a certain part of) one of the displays an information overload is eminent. This technology, however, should be introduced with care [Verhoeven 2000].

The Human Machine Interface agent is the actual cockpit display that provides the information on the user interface. It may take inputs from the user.

For a generic CA demonstration environment, we require a crew assistant independently from its operational environment. Obviously, a generic demonstration environment, especially a complex one as a crew assistant requires a number of general tools, like scenario generation tools and environment databases. The currently developed environment connects the tools to ITEMS, which provides a topographical scenario and an F-16 aircraft model. This enables the possibility to connect the crew assistant to e.g. a fly box, see figure 3, to the NLR's F-16 mock up simulator, and to the NSF, see figure 4.

Figure 3. Flybox and workstation configuration

Figure 4. National Simulation Facility

3.2 Reasoning with Uncertainty for Profile Recognition

Reasoning with uncertainty will be an important aspect of CA technology. Even the information from a fused sensor picture will usually contain unclear elements. To investigate possibilities of real-time reasoning with uncertainty, a profile recognition agent was developed.

Any crew assistant will gather information from its environment, process this information, and act upon it. Probabilistic methods for reasoning with uncertainty have gained a lot of interest in the last few decades. The introduction of Bayesian Belief Networks [Pearl 1988], [Jensen 1996] made practical application of probabilistic reasoning possible. Most applications have been targeted at decision support in the medical domain where the variables in the model typically have a few states and no real-time constraints exist. In contrast, the decision support systems for fighter pilots have to deal with many real-valued sensor readings that provide measurements every split second and that need to be processed in real-time [Van Gerwen 2000-2].

Suppose an aircraft has on-board sensors to identify profiles. In this example, different profiles are considered and the aircraft sensors can measure length, width, and speed of the objects that are sensed. However, sensor accuracy depends on weather conditions, in particular visibility, cloud coverage, and humidity. This scenario is modelled through a Bayesian Belief Network as given in figure 5. Each of the profiles modelled, has an a-prior probability distribution.

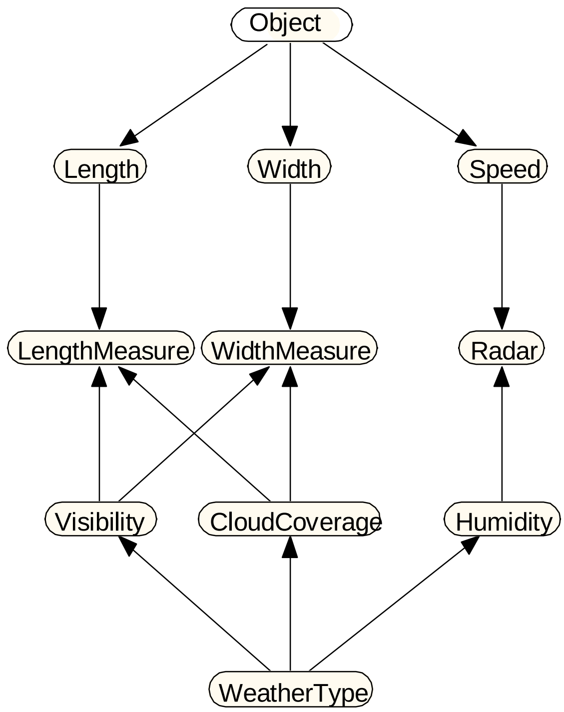

Figure 5. Bayesian Belief Networks for profile recognition

The goal of this research is to look into the possibility of creating an anytime algorithm for a Bayesian Belief Network. Anytime algorithms are algorithms that trade performance for time. As the amount of time is increased, an anytime algorithm improves the quality of the output. One of the features of anytime algorithms is that it can provide intermediate results at any moment, so that the available processing power and time can be regulated.

Propagating evidence in a Bayesian belief network can be a very time-consuming task (it is NP-hard). One solution might be an algorithm that uses state-space abstraction. We examined different AI techniques, like Breadth First, Breadth First Split, and Highest Belief First. Figure 6 gives the results of the different methods.

In the CA agent, we have shown that state-space abstraction in combination with a strategy such as Highest Belief First has interesting features required for an anytime algorithm. The proposed method outperforms simpler methods like Breadth First and Breadth First Split.

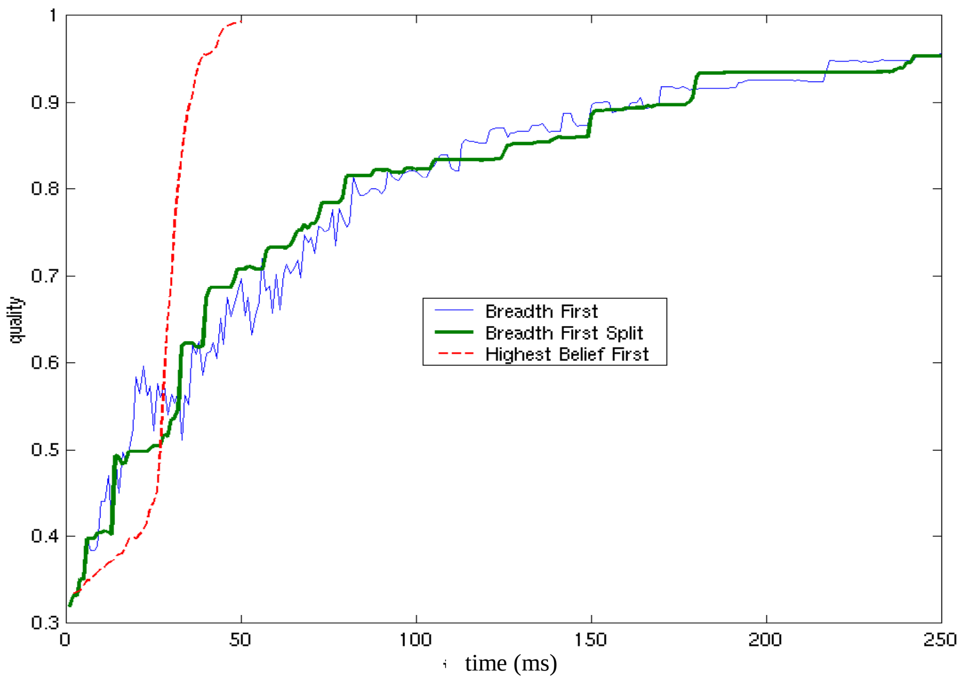

Figure 6. Running the BBN with different techniques to facilitate state space abstraction

3.3 Manoeuvre Prediction with Case Based Reasoning

The proposed Manoeuvre Prediction agent seeks to enhance the situation awareness of the pilot in a dogfight situation. Given information on the opponent’s aircraft, like position and speed, the agent will try to determine the manoeuvre it is performing. Using this information, the agent can predict the future path of the opponent’s aircraft. This information is then presented to the pilot, thus enhancing situational awareness. Benefits for this tool can be found in the earlier phases of a dogfight, where the opponent just enters visual range and the pilot is making an assessment of his radar and visual clues to determine the most beneficial counter actions.

The rapid changing environment in which such an application has to operate called for a strict real-time or any-time approach for the Manoeuvre Prediction agent. We also wanted to exploit the fact that every encountered dogfight involves manoeuvres that the application could use for future manoeuvre prediction.

It was decided, to use the case based reasoning technique from the field of artificial intelligence for implementing the Manoeuvre Prediction agent. The case bases reasoning technique will store cases (one manoeuvre is one case) in a database and provide means by which a newly encountered case can be compared to existing cases. The most similar case (manoeuvre) can be retrieved and used as source to indicated the encountered case. The newly encountered case will become part of the database for future use. This way of working is highly intuitive for humans, we learn from experience and try to recognise by comparing the current situation to past experiences.

The scientific challenge for implementing the Manoeuvre Prediction was to make the case based reasoning process work in real-time. We solved this by ordering the cases by individual elements of the manoeuvre (e.g. speed or distance from own-ship). Having an order in the database gives fast information where to look for the most similar case. In the end the search algorithm will quickly find the most similar case, but more importantly the algorithm will also perform well in anytime and will produce a fairly similar case, once interrupted.

Using the advanced software architecture of multi-agent technology the results from the Manoeuvre Prediction application are made available to the other applications (agents). These agents can use this information for their own purposes. The HMI agent will graphically display the information for the situational awareness of the pilot. The NCMM agent may use this information to take counter measures based on the enemy’s aircraft predicted position. The information may be sent to agents of nearby ground or airborne forces for their tactical decision aid or situational awareness.

3.4 NLR’s Counter Measure Manager (NCMM)

The NCMM agent determines the most effective use of actors to counter detected threats. Such an agent enables co-ordinated counter measures that can not be performed manually using the separate systems. Most notably, this involves counter measures combining jamming and chaff.

Furthermore, the manager can enhance effectiveness by combining counter measures to counter more than one threat simultaneously [Tempelman 1999], [Eertink 2000].

More information on the NCMM can be found in the second part of this paper, which describes an experiment to study the effects of decision support in the military cockpit and that has been carried out with the NCMM.

3.5 Display Development with NADDES

An HMI (Human Machine Interface) is designed with an NLR built tool, NADDES (NLR Avionics Display Development and Evaluation System) for increasing pilot situation awareness. NADDES is a development environment that has specifically been developed for the construction of avionics displays and as such, it provides a number of predefined components.

For the aforementioned demonstrations, separate HMIs have been developed. Since all demonstrations use the same development environment, they can easily be integrated to form one situation awareness picture for the pilot. The display manager agent decides which information to display on the available on-board HMIs.

An example of a NADDES developed HMI for the NCMM is given in figure 7.

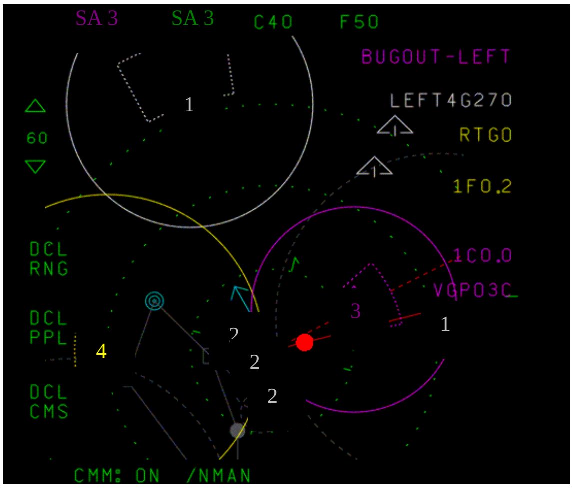

Figure 7 NCMM display

PART II: A THREAT MANAGEMENT DECISION SUPPORT EXPERIMENT

The second part of this paper describes a Crew Assistant and Situation Awareness experiment that has been carried out involving operational RNLAF pilots in the NSF simulator at NLR, Amsterdam. We will first give an elaborated overview of the NCMM tool that has been used and then focus on the details of the experiment.

The current military theatre becomes ever more complex and demanding for the pilot. This development is potentially threatening to the situational awareness of pilots and as such, to their safety. Solutions to keep track of the situation are sought, amongst others, in automated tactical decision aids. To what extend will pilots benefit from such systems? Will mission performance increase? What are the disadvantages? To answer these questions an experiment was designed, which will be described in this part of the paper. The experiment can be characterised best as an evaluation by fighter pilots of a threat management support system.

Figure 8. F-16 MLU cockpit

The experiment is performed in the NLR National Simulation Facility (NSF), see figures 4 and 8. This simulator is configured with an F-16 MLU cockpit. Mission profiles and controls used by the pilots during the experimental runs were recorded. Instrumentation and fittings allowed variables such as heartbeat frequency, eye point-of-gaze, pupil size, and eye blink rate to be measured.

Pilots flew through scenarios in which they encountered several threats. The task load between the scenarios was varied by the amount of surface threats that were implemented in the scenarios. In half of the test runs pilots had to deal with the treats manually, while in the other half an automated system initiated appropriate counter measures by itself.

Afterwards pilot performance, subjective and objective mental workload and the pilot appreciation of the automated threat management system were evaluated. For the experiment, we used the NCMM, mentioned in section 3.4 and further extensively described in chapter 4. Chapter 5 will present the experiment set up and describe the results.

4 NLR Counter Measure Manager (NCMM)

To countermeasure SAMs, the pilot has several options available. Generally, the best course of action is to avoid entering SAM rings, but this cannot always be avoided, especially when pop-up threats are encountered. Depending on the type of threat and its state, the pilot can jam or dispense chaff en flares. Usually, these counter measures are combined with a manoeuvre.

The NCMM agent determines the most effective use of actors to counter detected threats. Such an agent enables co-ordinated counter measures that can not be performed manually using the separate systems [Tempelman 1999], [Eertink 2000]. A schematic representation of the manager's architecture is supplied in figure 9.

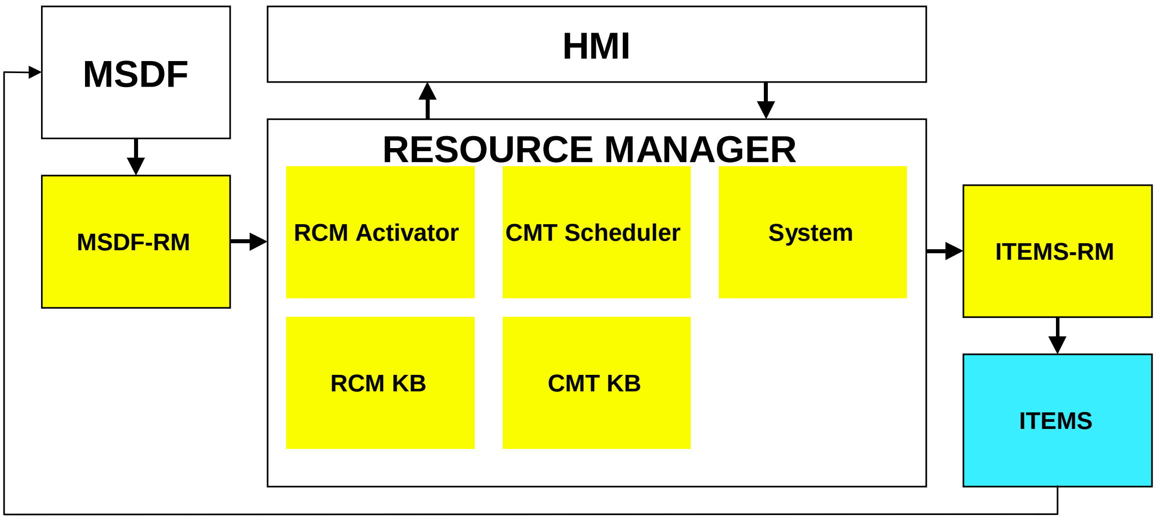

Figure 9. The NCMM in the simulation environment.

The MSDF agent delivers environment data, most notably sensor tracks and threat information, to the resource manager. The resource manager is the core of the NCMM. It consists of two rule-based knowledge bases: the Reflex Counter Measure (RCM) Knowledge Base and the Counter Measure Technique (CMT) Knowledge Base. The first associates sensor tracks directly to single counter measures (e.g., chaff, flare, a jamming technique, a manoeuvre), in situations where immediate action is required. The latter connects threats, i.e., fused sensor tracks, under certain positional conditions to a series of counter measures, after which the dynamically planning CMT Scheduler fits these into the existing counter measure schedule.

An example of the represented CMT knowledge is given in table 1. Rule number 12 (highlighted in the table), for example, represents what can be done to counter a threat of type SAM1 in track (T) mode, which has threat level (lethality) 4 on a scale of 0 to 10. The SAM1 is detected by two sensors, the Radar Warning Receiver (R) and the ALQ (J). With an expected effectiveness of 8 on a similar scale, it can be countered by a combination of Range-Gate Pull-Off (a jamming technique) followed by dispensing 4 bundles of chaff with an interval of 0.2 seconds (4C0.2), if the condition on the threat's position is fulfilled.

The knowledge in the resource manager is highly flexible. It can be adapted easily to include newly constructed counter measure techniques and it can be modified to reflect the availability of other agents in the aircraft in which the NCMM is running.

Various operational modes are available in the NCMM. These determine the availability of assets in various circumstances. For example, it can be necessary to not use jamming counter measures, as the enemy can detect these. Selecting the operational mode 'Run Silent' will then take care of this. Furthermore, the NCMM agent supports system modes, determining the amount of automation of the system. These vary from manual, in which case only advises are given, to fully automatic, in which case all counter measures except manoeuvres are executed automatically and in time. For reasons of pilot convenience, manoeuvres will only be advised.

The NCMM was evaluated and validated in a semi-realistic simulation environment called ITEMS. Various scenarios were flown in various modes. A simple scenario, in which no threats overlap, is shown in figure 10. The flexibility of the manager was demonstrated by running it both in a simulated F-16 and in an Orion P3, the latter having far less counter measure possibilities. The NCMM demonstrated improved effectiveness and efficiency of using countermeasures against threats in a number of multi-threat scenarios, compared to manually threat countering. Advantages are that series of counter measures that require exact timing with respect to each other can be executed automatically, that the NCMM can combine counter measures to counter multiple threats, and that the NCMM can take the effect of a counter measure against a threat to other threats into account in highly complicated situations.

ID	*Threat*	*Mode*	*TL*	*Sensors*	*Effectiveness*	*GCMT*
1	SAM1	S	3	R	5	OT
CONDITION: None						
# Simple example: SAM1 search radar (low TL) detected by RWR only; Turn to evade the site.						
2	SAM1	S	3	R+J	8	N1S
CONDITION: None						
# As above, only now the site is also detected by the ALQ, so jamming can be used (Noise).						
12	SAM1	T	4	R+J	8	RGPO1C+4C0.2
CONDITION: Threat at (20°<F<60°)∨(300°<F<340°)						
# Sam is tracking the aircraft. Combination of RGPO and chaff is effective, but only at certain azimuth angles						
32	SAM1	L	9	R+J+MA	8	VGPO1
CONDITION: Time Till Intercept≥5s						
# see number 34.						
34	SAM1	L	10	R+J+MA	5	6GturnInto
CONDITION: Time Till Intercept<5s						
# Missile is launched, detected by MAW. Assuming semi-active missile, VGPO can be attempted. If this fails (TTI<5s), perform last ditch manoeuvre						

Table 1. Part of the CMT knowledge base

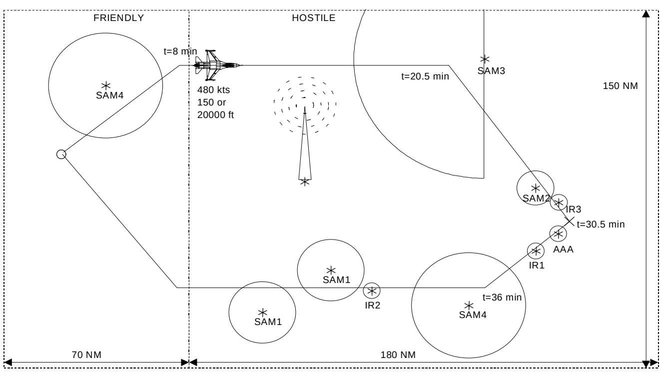

Figure 10. Example scenario for NCMM validation.

5 A threat management support experiment

This chapter describes the experiment set up and the results.

5.1 Experiment Description

The purpose of the current experiment is to demonstrate the advantages and disadvantages of a CA. The experiment will show whether automation about threat management tasks is beneficial to the mission compared to the current situation, in which pilots have to perform these tasks without such support. To define the additional value of the support, the mission performance, the subjectively and objectively measured fatigue and workload of the pilots has beeen investigated. NCMM served as the threat management support system (the CA).

The experiment was designed to answer the following specific questions:

- Does decision support improve pilot performance (fighter performance, mission effectiveness), especially in situations in which a great deal of the pilot’s attention is needed for other tasks (high taskload saturation)?
- Will pilots appreciate the tool when they can be convinced that the pilot always remains in control?
- Will the integrated way of information presentation, that is part of the CA interface in the current experiment, aid the pilots in gaining and remaining their situational awareness?
- Will pilots get a better understanding and appreciation of the tool after they are given time to test it thoroughly?
- Will pilots either experience a workload decrease, a performance increase, or a combination of both as a result of the CA?
- The moments with the highest workload are needed here. Heart rate during those moments should be compared between the CA on and the CA off.

Nine operational male F-16 pilots from the Royal Netherlands Airforce participated each for one day in the experiment. The right Multi Function Display (MFD) was reserved entirely for NCMM. Swapping the NCMM page, or removing it from the MFD, was not possible. The pilot was informed about NCMM system mode before the run started.

During half of the runs NCMM operated in the standby mode. In this mode NCMM provides explanatory information about the location and type of the surface threats and the flight path only. In this mode NCMM does provide the same information as what is now available on the current F-16 MLU Multi Function Displays in combination with the Radar Warning Receiver (RWR). The pilot selected and executed the counter measures against the threats manually. He had to actively dispense chaff and flare and select the jamming mode. Manoeuvres had to be executed manually.

During the other half of the runs NCMM operated in the automatic mode. In this mode NCMM decides when to expend chaff and flare and dispenses them automatically. The pilot can dispense additional chaff and/or flare manually in this mode. Also the appropriate jamming modes are selected automatically. In addition, NCMM also advises about appropriate manoeuvring. However, the execution of the manoeuvres has to be done by the pilot.

The pilots' task was to fly six low altitude weapon delivery missions. Each run had the same mission goals but the mission profile was different every time. Pilots were instructed to stay to the assigned flight path as much as possible. They were also asked to fly low altitude, though not too low so that they would not fly below radar coverage. The pilots were recommended to use NCMM advice if they felt that it was tactically sound, but to otherwise execute their own plan. Each scenario consisted of a short flight (duration was about ten to fifteen minutes) in which the subjects encountered a number of threats. During the runs several threats could pop up. Given the nature of NCMM it was decided to use, primarily, surface threats. Pre-planned threats and steer points were chosen such that the missions that the pilots were flying could well be compared. Pop-up threats always combined to a pre-planned threat in such a way that a logical course of action would follow. An example of a mission with pre-planned threats is given in figure 11. The dashed circles represent the threats with a numbered classification (fictive). The line is the route to be followed, including numbered way points. Way point number five is the target.

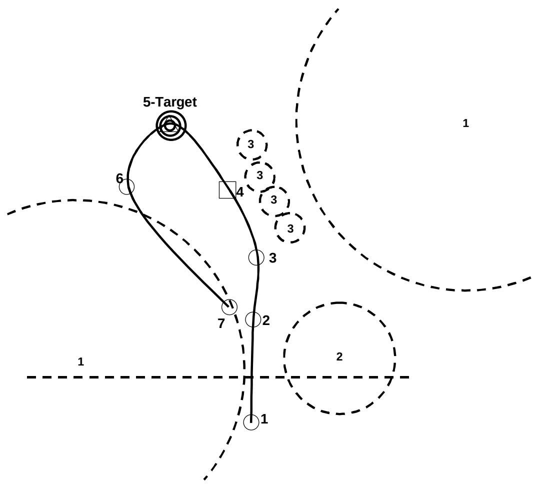

Figure 11. Example mission with pre-planned threats.

5.2 Experiment design

In one condition NCMM provided decision support (automatic mode). This condition was compared to a condition in which NCMM provided explanatory information about the threats only (standby mode) but no advice was offered.

The effect of NCMM was investigated both under high task load and low task load conditions. During half of the runs the pilot was flying in a low workload environment. A limited amount of surface threats was present during those runs. During the other half of the runs a high workload environment was presented. In these scenarios more surface threats were present and enemy fighter aircraft could be encountered.

The benefits of NCMM were compared between the two NCMM modes and the two levels of task load. The above means that the pilots had to fly scenarios in four different configurations.

Since pilots had to fly six runs each and because it was undesired that they transferred experience between scenarios, three different mission profiles were developed. The runs were assigned over these profiles and the four experimental conditions. This approach ensured that pilots never flew the same run twice. It also ensured that they flew three runs with NCMM in standby and three in automatic mode and it finally ensured that they flew three runs in a high and three in a low workload condition.

5.3 Measurements and equipment

During the missions, all information that was exchanged between the agents and between the agents and the pilots was logged. Besides, psycho-physiological measurements were taken and the pilots were asked to fill out questionnaires at several moments during the day.

In close co-operation with operational experts, simulator events have been valued in terms of performance. Based upon the hypotheses a selection of simulator and NCMM variables was made, in order to be recorded. These comprise amongst others: countermeasures made by NCMM (in automatic mode), countermeasures made by pilot (in stand by mode), mission duration, amount of time spent in search or track of threats, deviations from the flight path, and weapon delivery events.

Heart rate

In addition to the simulator logfiles, other objective indicators of mental workload, namely psychophysiological parameters, were recorded by the Vitaport 1 system. Those comprise the electrocardiogram (ECG) and respiration. ECG was measured with three Ag/AgCl electrodes. One was attached approximately 4 cm. above the jugular notch of the sternum, one at the apex of the heart over the ninth rib, and the ground electrode was placed above the right iliac crest. The ECG was used to determine the Heart Rate (HR) and Heart Rate Variance (HRV). Respiration was measured using a pair of strain gauge transducers around the chest and the abdomen, so that the influences of respiration rate, and speech, on HRV could be filtered out later. During the offline data analysis HR artefact correction was carried out according to a procedure described by [Mulder 1988].

Eye Point-of-Gaze

Eye Point-of-Gaze is the point on a predefined surface were an imaginary line coming straight from the centre of the eye crosses that surface via the lens of the eye. As such this is the central point in the pilot’s field of vision. This point was measured by means of an EPOG-recorder called GazeTracker [Mooij 1996]. The duration that a pilot looks at a particular area of interest, is called a “dwell”, which was stored in a computer file. In addition to the dwell-times the scanning pattern, the amounts of fixations, the pupil diameter, and eye the blink activity (which permits blink rate, duration, and other measures to be derived) of the pilots’ left eye were recorded as indicators of fatigue and mental and visual workload [Harris 1986], [Wilson 1987], [Wilson 1993], [Stern 1994]. The scanning behavior was considered to be an indicator of the pilot’s mental state and focus of attention. The commonly accepted assumption was made that if a pilot looks at a particular area of interest he is mentally processing the data that are manifest at that area.

5.4 Results

The pre- and post experiment questionnaires demonstrates that pilot opinion, regarding a number of NCMM related items, had changed after using the NCMM in the experiment.

In figure 12, the pilot ratings before and after the experiment are displayed. The left side of the graph shows the answers to the “system design issue” questions. The right half shows the answers to the “system application (use) issues”. The red line represents the average of all pilot responses to the pre-experiment questionnaire. The green line represents the average of all pilot responses to the post-experiment questionnaire. Distances between the two lines may be seen as an indication of the “change of mind” of the pilots after using NCMM in the NSF for several hours. While often the trends of both lines are the same, there are differences as well. Roughly speaking the differences (distances between the two lines) comprise the following issues.

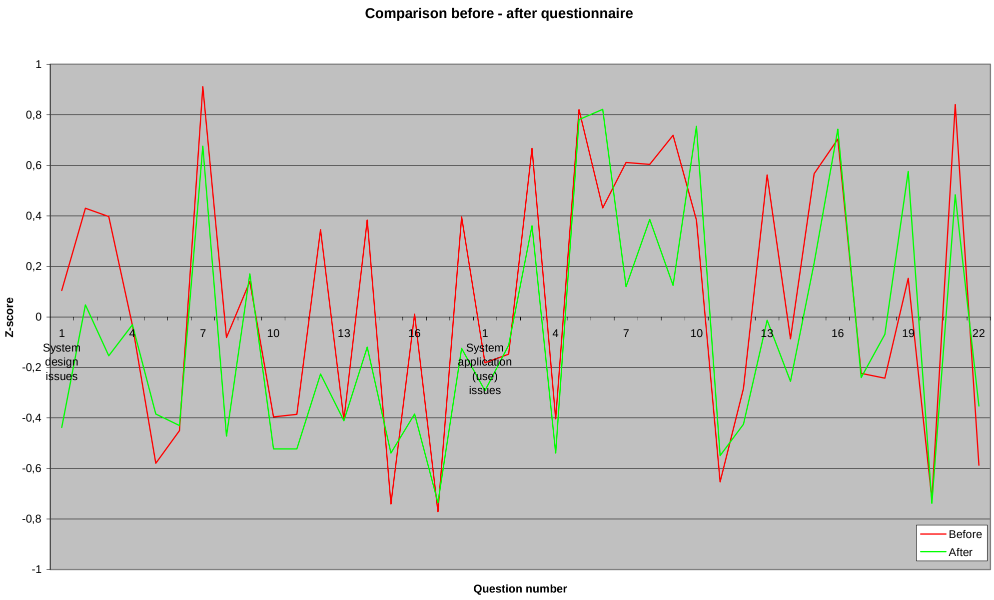

Figure 12. Responses to questionnaires before and after the experiment. Answers were first transferred to Z-scores[1]*. After that, the average over all pilots was calculated, and plotted in this figure.*

With respect to the system design related questions, it was observed that the pilots were more convinced, after using NCMM, that:

- It performs like a real pilot.
- Integration in the aircraft may be adequate.
- It does not show too much irrelevant/distracting details.
- NCMM is capable of taking pilot personal preferences into account.
- NCMM is sufficiently sensitive to specific mission demands.

The most important results concerning the system application (use) were that pilots, after using NCMM, were more convinced that:

- They have confidence in the system and will as such use it.
- They will not necessarily (eventually) loose EW related skills when using NCMM.
- They will not pay too much attention to NCMM.

Situational Awareness (SA) as rated by the pilots themselves and by an observer is visualised in figure 13

[1] Z scores are standardised scores. They were calculated using the following formula: Z score = (raw score - mean) / standard deviation.

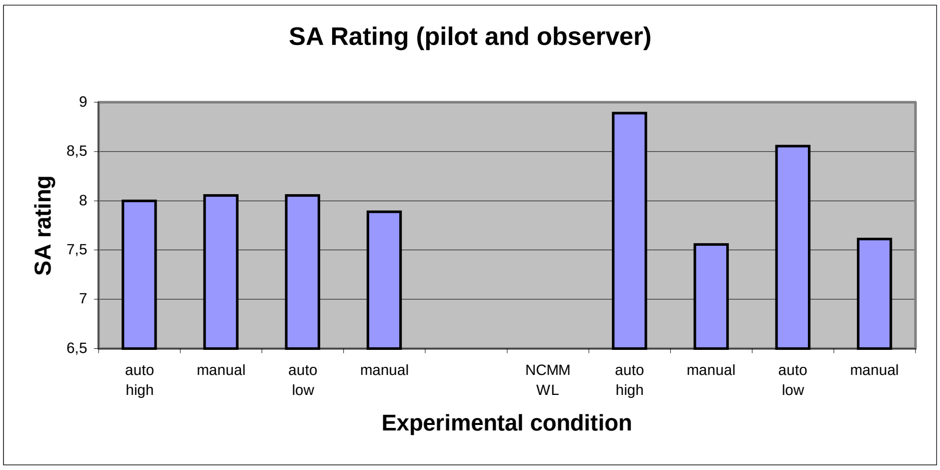

Figure 13. Pilot and observer ratings of pilot situational awareness.

Note that pilots considered their SA at approximately the same level during all four conditions, but that the observer, who was aware of everything that happened in the scenarios (even those things that pilots could never be aware off) rated the pilot SA higher during the missions were NCMM was running in automatic mode.

One of the performance indicators that was monitored was the jamming mode the pilots selected versus the jamming mode that was selected by NCMM. While watching the pilots perform, it already became very likely that pilots frequently forgot to select the appropriate jamming mode, while NCMM selected the right jamming mode as soon as it has identified a new (high priority) threat.

6 Conclusions from the POWER project

With the increase in aircraft speed and on-board technological developments and the increasing complexity of military environment and missions, the workload of the fighter pilot is rapidly increasing. Crew assistant technology is aimed at reducing the pilot's workload through enhanced situational awareness.

The POWER project provided a large scale demonstrator for crew assistant technology. An architecture, based on multi-agent technology has been set up, where different examples of crew assistants have been integrated:

- A profile recognition detects profiles in the assembled picture from the multi-sensor data fusion process.

- A manoeuvre prediction can be used in dogfight situations to predict and anticipate enemy aircraft's manoeuvres.
- NCMM is the NLR Counter Measure Manager to assist the pilot in taking counter measures against ground threats.

The focus of the project has been decision support in operational fighter aircraft scenarios through the integration of AIP and HF aspects in the military cockpit. We have shown the integration of these areas by examining different AIP techniques and their integration in the cockpit. Display design has been carefully taken place to take the HF aspects into account. A step has been made in the quantitative and qualitative effects of on-board decision support functions in an experiment where operational F-16 pilots participated.

We examined the possibilities for real-time and especially any-time reasoning in on-board application. Any-time algorithms provide the possibility to interrupt the reasoning process at any moment thus enabling optimal processor performance and use. Promising techniques are Bayesian Belief Networks and case based reasoning.

Future work will be directed to the maintenance of the architecture provided and to the further integration of agents, both functional and for system control and monitoring. More work needs to be carried out to reasoning with uncertainty. The environment can be used to facility more experiments.

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